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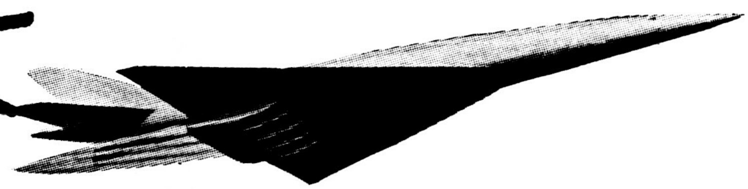
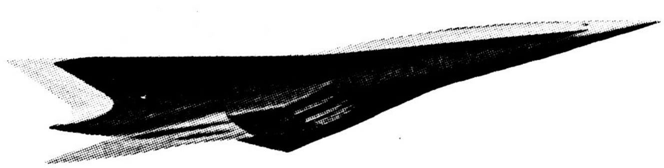


PERFORMANCE POTENTIAL

HYDROGEN FUELED, AIRBREATHING CRUISE AIRCRAFT (U)

FINAL REPORT
VOLUME 1
SUMMARY



GENERAL DYNAMICS
Convair Division

PERFORMANCE POTENTIAL OF HYDROGEN FUELED, AIRBREATHING CRUISE AIRCRAFT

FINAL REPORT

VOLUME 1 - SUMMARY

REPORT NO. GD/C-DCB66-004/1

Prepared for

NATIONAL AERONAUTICS & SPACE ADMINISTRATION
MISSION ANALYSIS DIVISION
MOFFETT FIELD, CALIFORNIA

by

GENERAL DYNAMICS
CONVAIR DIVISION
SAN DIEGO, CALIFORNIA

CONTRACT NAS 2-3180

30 September 1966

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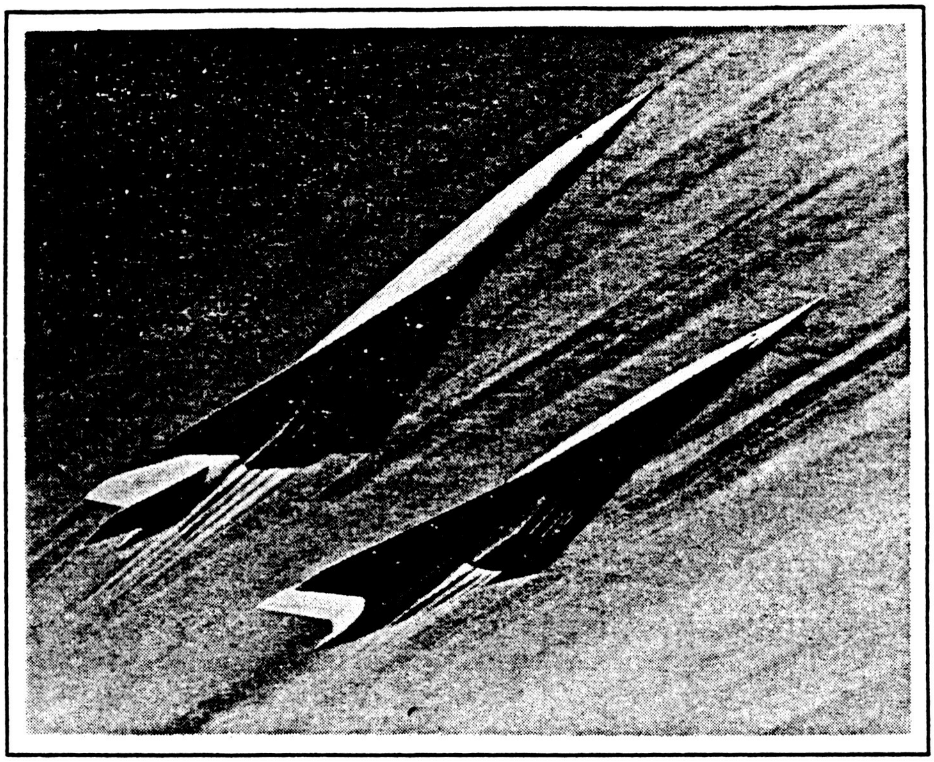

TYPICAL HYDROGEN FUELED, COMMERCIAL TRANSPORTS

FOREWORD

Contract NAS 2-3180 was a study of the performance potential of a liquid hydrogen fueled, commercial transport. This study was performed at General Dynamics Convair, San Diego from September 1965 to July 1966. Frank E. Jarlett was Project Leader and Christopher J. Cohan was Assistant Project Leader. The contract was administered by the Mission Analysis Division of the National Aeronautics and Space Administration, Moffett Field, California. Technical monitors were Richard H. Peterson and Thomas J. Gregory.

The final reports of the study are as follows:

Volume 1	Summary.
Volume 2	Phase I Studies.
Volume 2A	Phase I Propulsion Studies. (Confidential)
Volume 3	Phase II Technical Studies. (Confidential)
Volume 4	Final Studies. (Confidential)

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1.0 INTRODUCTION

The NASA Mission Analysis Division, Moffett Field, California, awarded Contract NAS2-3180 to General Dynamics Convair, San Diego, starting 7 September 1965. This contract was to study the "Performance Potential of Liquid Hydrogen Fueled, Airbreathing, Cruise Aircraft". The contract was for 74 man-months of effort over the nine month duration of the contract.

1.1 OBJECTIVES

The objectives of the study are shown in Table 1. Items 1 and 2 were defined as Phase I and Items 3 through 6 as Phase II. Phase I was completed during the first four months of the study.

1.	TO INVESTIGATE A WIDE VARIETY OF LH_2 FUELED, AIRBREATHING, CRUISE AIRCRAFT.	PHASE I
2.	TO SELECT TWO PROMISING CONFIGURATIONS.	
3.	TO EXAMINE, IN DETAIL, THE PROBLEM AREAS OF THE SELECTED CONFIGURATIONS.	PHASE II
4.	TO PROVIDE A DETAILED DEFINITION OF THE FINAL CONFIGURATIONS.	
5.	TO PERFORM SENSITIVITY STUDIES.	
6.	TO DEFINE CRITICAL RESEARCH AREAS.	

TABLE 1. STUDY OBJECTIVES

1.2 GROUND RULES

The ground rules for the study are shown in Table 2.

FUEL:	LIQUID HYDROGEN
PROPULSION:	AIRBREATHING
MISSION:	COMMERCIAL TRANSPORT
OPERATIONAL:	1985-2000 TIME PERIOD
CRUISE MACH:	3 TO 12
SONIC BOOM:	≈ 2 PSF DURING CLIMB 1.5 PSF DURING CRUISE
TAKE-OFF:	160 KNOTS & ≈10,500 FT.
LANDING:	135 KNOTS & ≈8,000 FT.

TABLE 2. GROUND RULES FOR STUDY.

1.3 ORGANIZATION OF THIS REPORT

This report is organized along the lines that the study was conducted, i.e.,

Section 2.0 Shows the results of the broad, parametric Phase I studies and the selection of the two most promising configurations.

Section 3.0 Shows the two selected configurations and the results of the detailed technical studies in Phase II.

Section 4.0 Shows the final study configurations, sensitivity data and critical research areas.

Section 5.0 Study Conclusions.

2.0 PHASE I STUDIES

Phase I extended over the first four months and was a broad parametric study of the overall characteristics of a liquid hydrogen fueled, commercial transport. The purpose of these studies was to select two promising configurations which were then used as the basis for the Phase II detailed technical studies.

About 80% of the Phase I effort was spent in finding the best combinations of configuration shape, propulsion and trajectory. Minimum takeoff weight was used as the main criterion of judgment. Figure 1 and Figure 2 show the five baseline configurations that were used in Phase I. Table 3 shows the selected vehicle geometry, propulsion system and trajectory data.

Figure 3 summarizes the effect of cruise Mach No. and shows that the best cruise Mach number for the turbojet/ramjet is about Mach 6.0. For the turbojet/ramjet/scramjet the best cruise Mach No. is 8.0. A Mach 3.0 turbojet-powered aircraft was also studied, but did not appear competitive.

Combining the above configuration/propulsion/trajectory data with the results of mission, cost and sonic boom studies, the overall results of Phase I are shown in Table 4. The mission/cost studies indicated that a range of 5,000 nautical miles and a passenger capacity of 200 were attractive compromises. Based on the takeoff weight, sonic boom and cost, the Delta Wing and Blended Body/Double Delta configurations were selected. The Variable Sweep wing was retained for limited Phase II studies on abort and subsonic hold. The Blended Body/Variable Sweep and Scramjet configurations were dropped because of their high takeoff weight and high operating cost.

3.0 PHASE II TECHNICAL STUDIES

The objective of the Phase II studies was to investigate in more detail the most significant technical areas of the configurations selected at the end of the Phase I studies. The initial task was to point design these configurations for use in the technical studies.

3.1 PHASE II CONFIGURATIONS

The Delta Wing and Blended Body configurations are shown in Figure 4. Also shown is typical flight profile data for the 5,000 nautical mile (less reserves) mission.

3.2 AERODYNAMICS

Delta Wing Configuration.

In meeting the takeoff and landing speeds and distances shown in Table 2, the wing

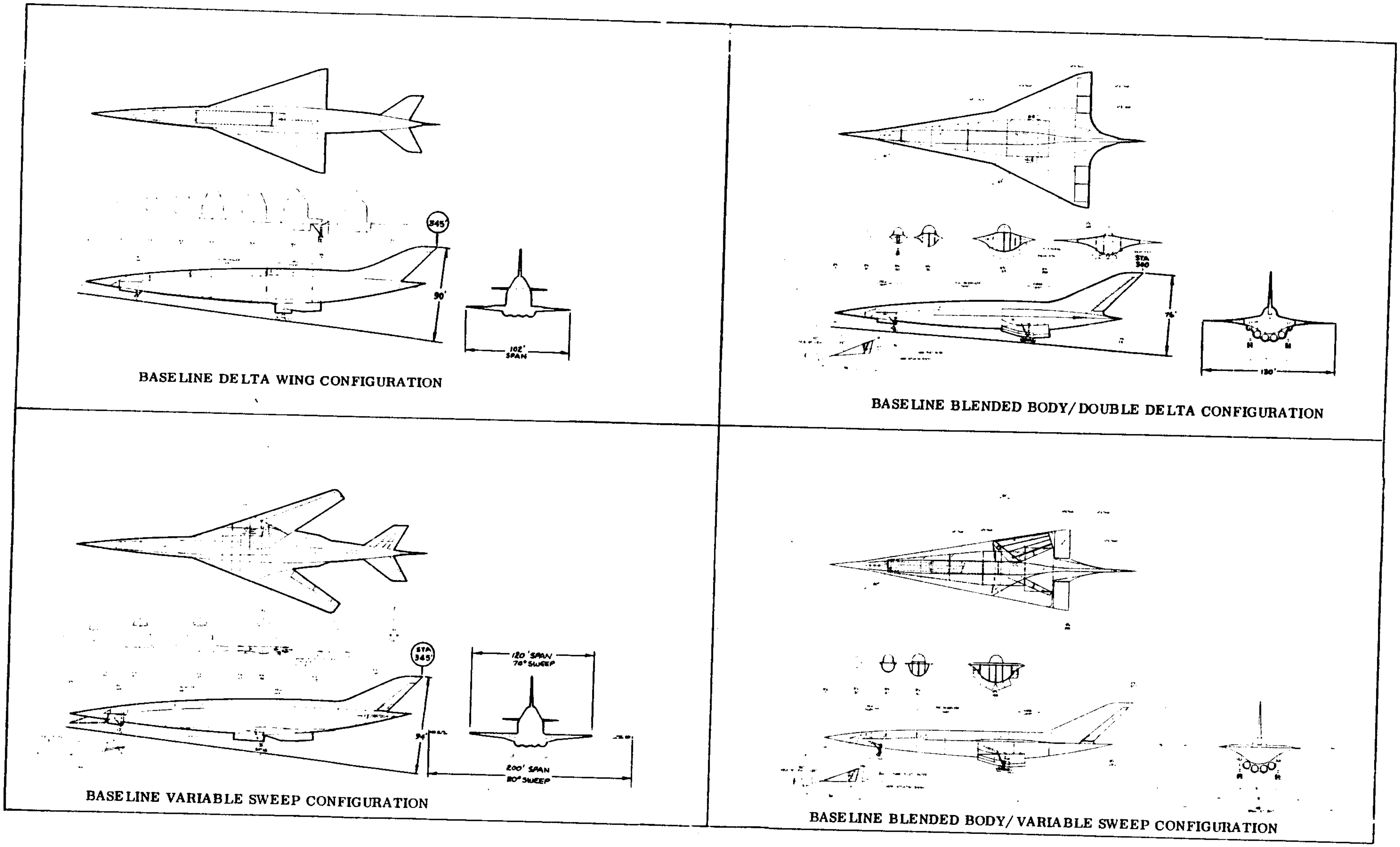


Figure 1. Baseline Configurations.

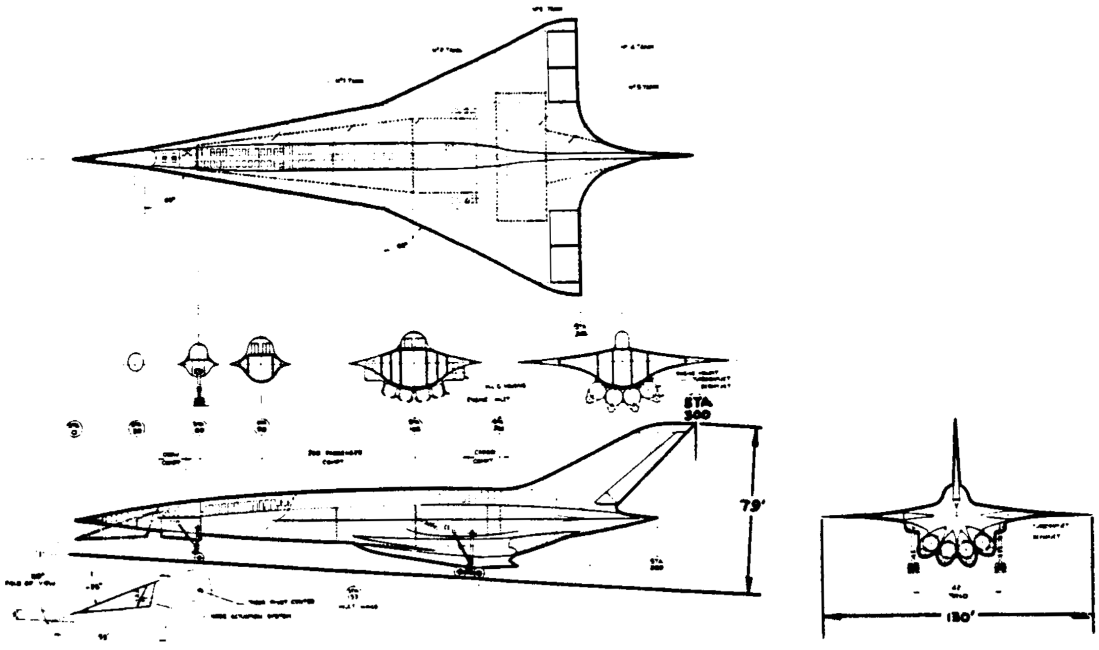


Figure 2. Scramjet Configuration.

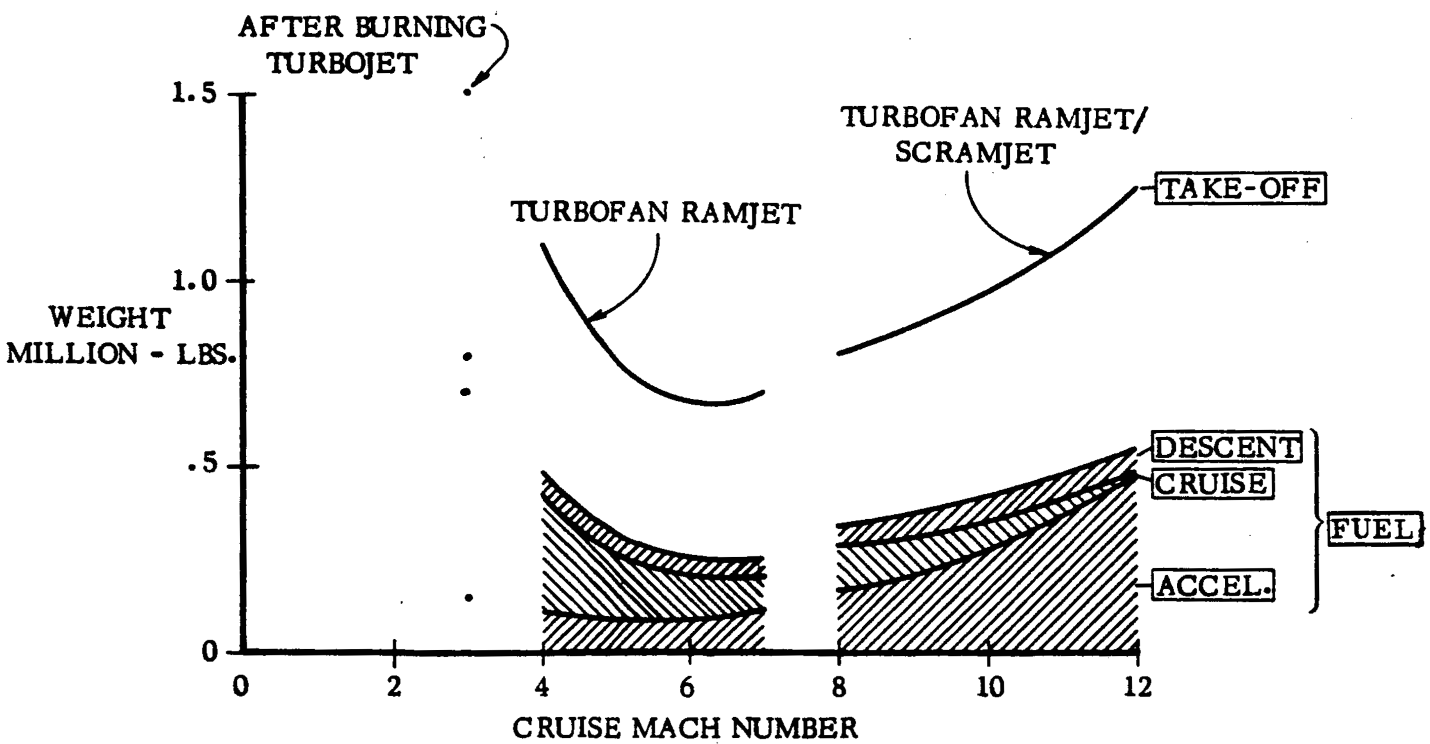


Figure 3. Effect of Cruise Mach No.

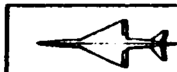
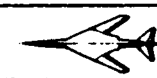
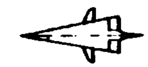
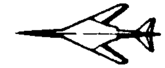
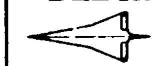
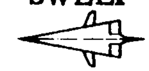
				
WING/PLAN LOADING (PSF)	81/-	125/-	-/35	130/82
ASPECT RATIO	1.45	1.47/6.5	1.5	.67/6.1
THICKNESS	.06	.05	-	-
SWEEP	70°	70°	80°/65°	80°
BODY FINENESS	12	12	-	-
PROPULSION M=0-3	TURBOFANRAMJET			
CRUISE MACH NO.	≈ 6			
TRAJECTORY: TRANSONIC	ΔP ≈ 3 PSF (M=1.4 @ 45,000 FT)			
DYNAMIC PRESS.	2000 PSF			
INLET PRESS.	130 PSI			
DESCEND	≈ L/D MAX			
LOITER	100 N.M. + 1,000 SECS. @ M = .9 @ 40,000 FT			
TAKE OFF WEIGHT (LB)	537,040	602,483	543,797	874,073

TABLE 3. DATA FOR CRUISE MACH 3-8.

		BLENDED BODY		
	DELTA WING 	VARIABLE SWEEP WING 	DOUBLE DELTA 	VARIABLE SWEEP 	SCRAMJET 
WING LOADING (PSF)	81	125	35	130	35
PROPULSION	TURBOFANRAMJET				+SCRAMJET
CRUISE MACH	6	6	6	6	8
TAKEOFF WEIGHT (LB)	537,040	602,483	543,797	874,073	846,927
RANGE	5,000 NAUTICAL MILES				
NUMBER OF PASSENGERS	200				
MAX. SONIC BOOM (PSF)	3.2	3.7	3.1	3.4	3.4
*TOTAL OPERATING COST (CPSM)	6.9	8.0	6.4	9.6	9.5
SELECT	●		●		
RETAIN		●			

* Liquid hydrogen @ 20¢/lb.

TABLE 4. PHASE I CONFIGURATION COMPARISON.

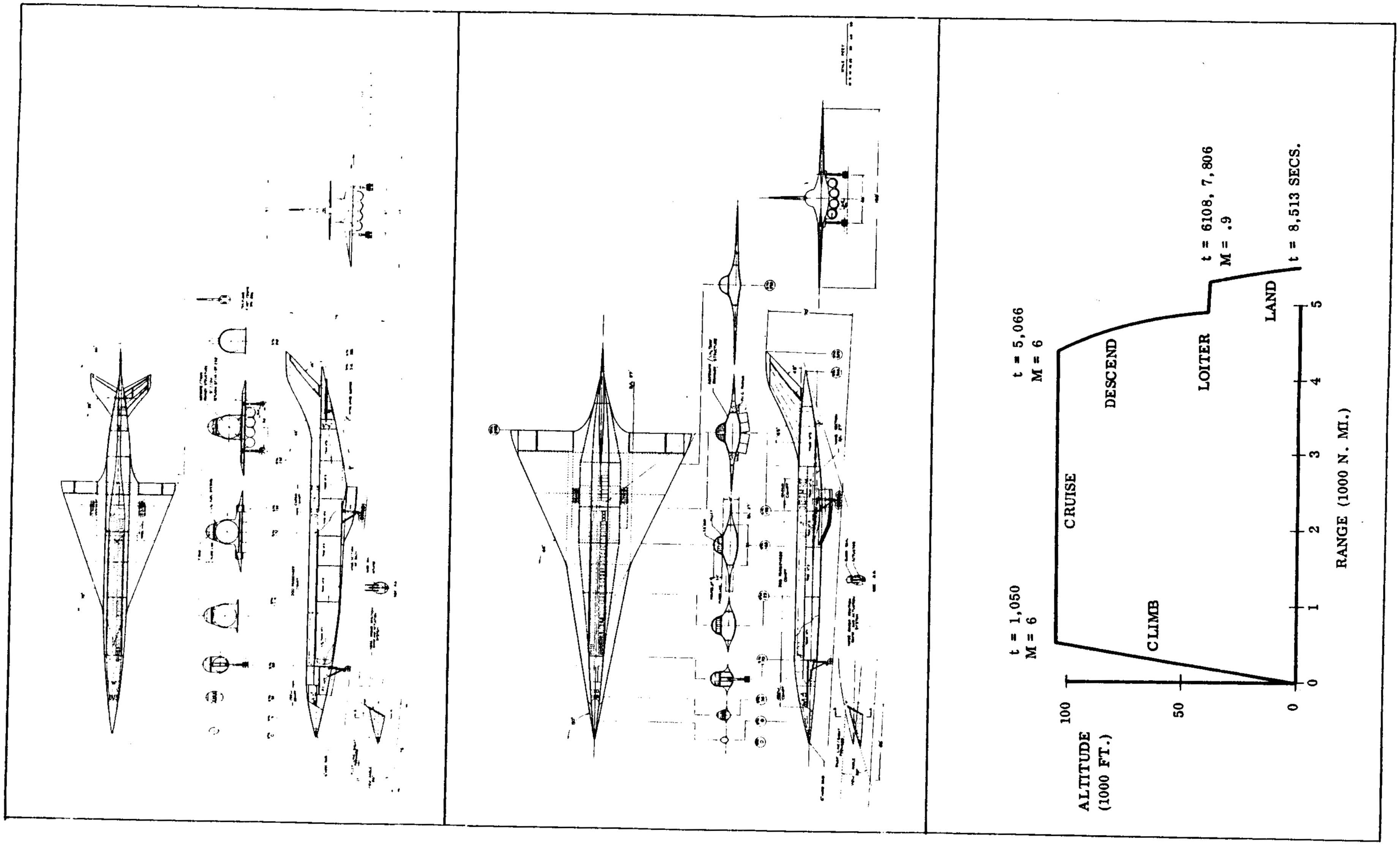


Figure 4. Phase II Configurations.

area, wing shape and flap configuration are sized for the takeoff speed requirement. Table 5 shows the wing planform and flap settings for the delta wing configuration. The maximum values of lift/drag for the configuration shown in Figure 4 are shown in Figure 5. Also shown are the values of L/D MAX that might be obtained by configuration refinements such as body and wing warping.

Blended Body Configuration.

Figure 6 shows the planform wing loading and lift coefficient that are needed to meet the takeoff speed requirement of 160 knots. Figure 7 shows the values of maximum lift/drag ratio for the configuration shown in Figure 6. The potentially attainable values with wing and body warping are also shown.

3.3 PROPULSION

Installation.

To keep the inlets within the wing pressure field and to meet the requirements for center of gravity location, the four engine propulsion package shown in Figure 4 was selected. The turboramjet/two dimensional, variable geometry inlet arrangement shown in Figure 8 was analyzed to determine its installed performance and its cooling requirements during cruise. This arrangement was essentially a pod mounted below the under surface of the wing. Because the engine diameter was about twice the depth of the inlet cowl this resulted in significant cowl and nacelle wave drags. Burying the engine as shown in Figure 9 eliminated these drags and improved the specific fuel consumption during cruise by $\approx$ 15% which reduced the takeoff weight by $\approx$ 25%.

Inlet/Engine Cooling During Cruise.

Table 6 shows the inlet and engine cooling requirements during cruise. It is seen that, at Mach 6.0 cruise, the cooling/thrust fuel flow is between 1.11 and 1.19. The higher values occur at the end of cruise and for the buried type of installation shown in Figure 9. To keep within the assumed metal temperature of 1,500^{o}F, either (a) the cruise Mach number must be reduced from 6.0 to about M = 5.3, or (b) the engine cooling requirements must be reduced.

Abort.

The abort mission has propulsion implications. A 5,000 nautical mile, over-water route may, because of a malfunction, require the aircraft to decelerate and descend from Mach 6.0 and 100,000 ft. altitude and complete the flight in a less hostile environment, e.g., Mach 0.9 at 40,000 ft. Two methods of obtaining the required subsonic range are: (a) adding fuel reserves, or (b) improving the subsonic lift/drag ratio with a high aspect ratio variable sweep wing, but both methods give unacceptably large increases in takeoff weight. The most competitive approach is to design an engine

Λ_{LE} = 65°	
W/S_{TO} = 78 psf	C_L AT LIFTOFF = 1.05 , $\alpha = 15°$
FLAP SETTINGS: TAKEOFF $\delta_{f_{TE}} = 35°$ LANDING $\delta_{f_{LE}} = 45°$ $\delta_{f_{TE}} = 20°$	$S_{LE} = S_{TE} = .10\ S_W$
SPEED: LIFTOFF 145 KNOTS LANDING 135 KNOTS	(LIFT=WEIGHT @ $V = .9\ V_{TO}$) (WEIGHT AT LANDING = $.63\ W_{TO}$)

TABLE 5. DELTA WING CONFIGURATION - WING DATA.

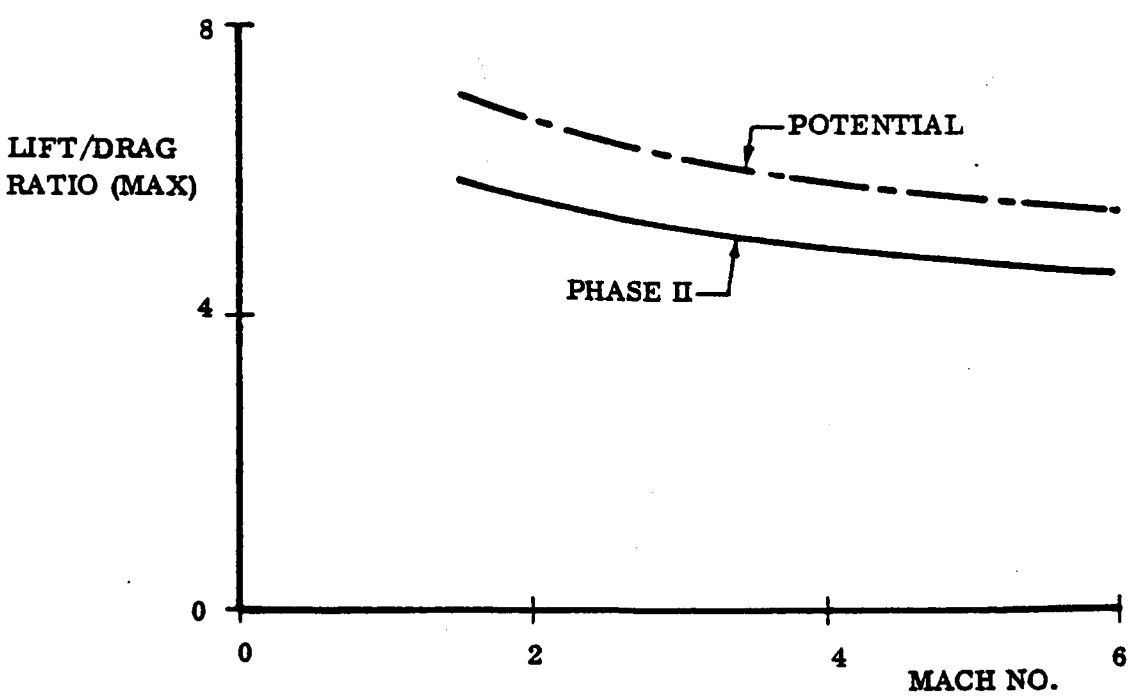


Figure 5. Maximum Lift/Drag Ratio - Delta Wing Configuration.

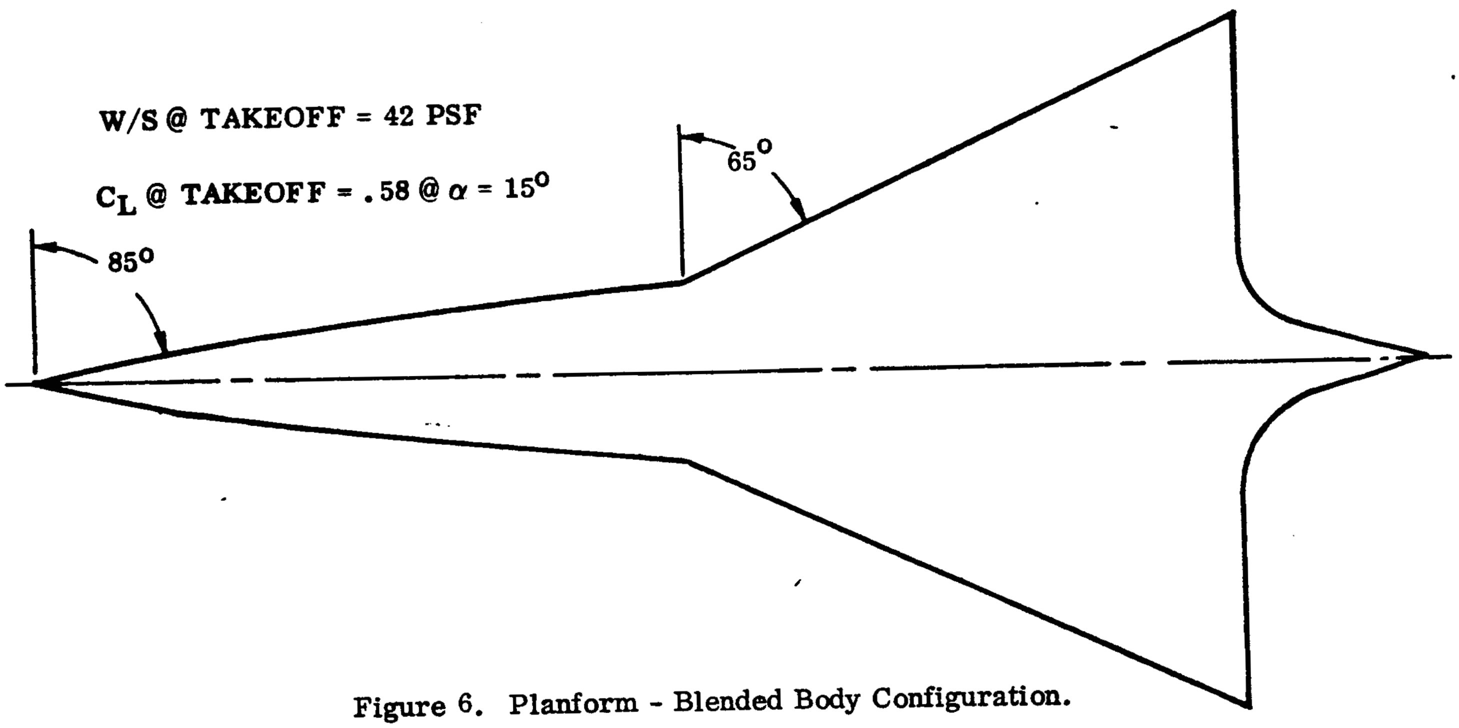


Figure 6. Planform - Blended Body Configuration.

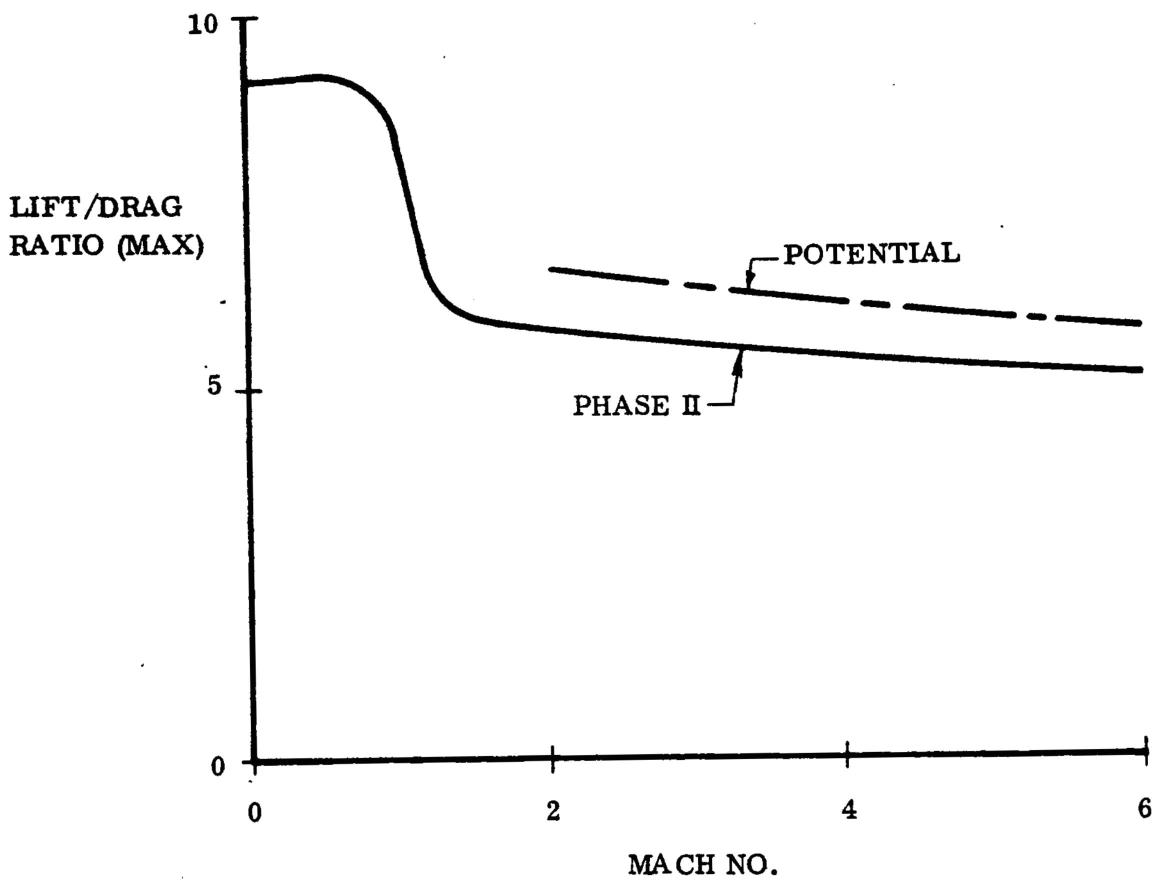


Figure 7. Maximum Lift/Drag Ratio - Blended Body Configuration.

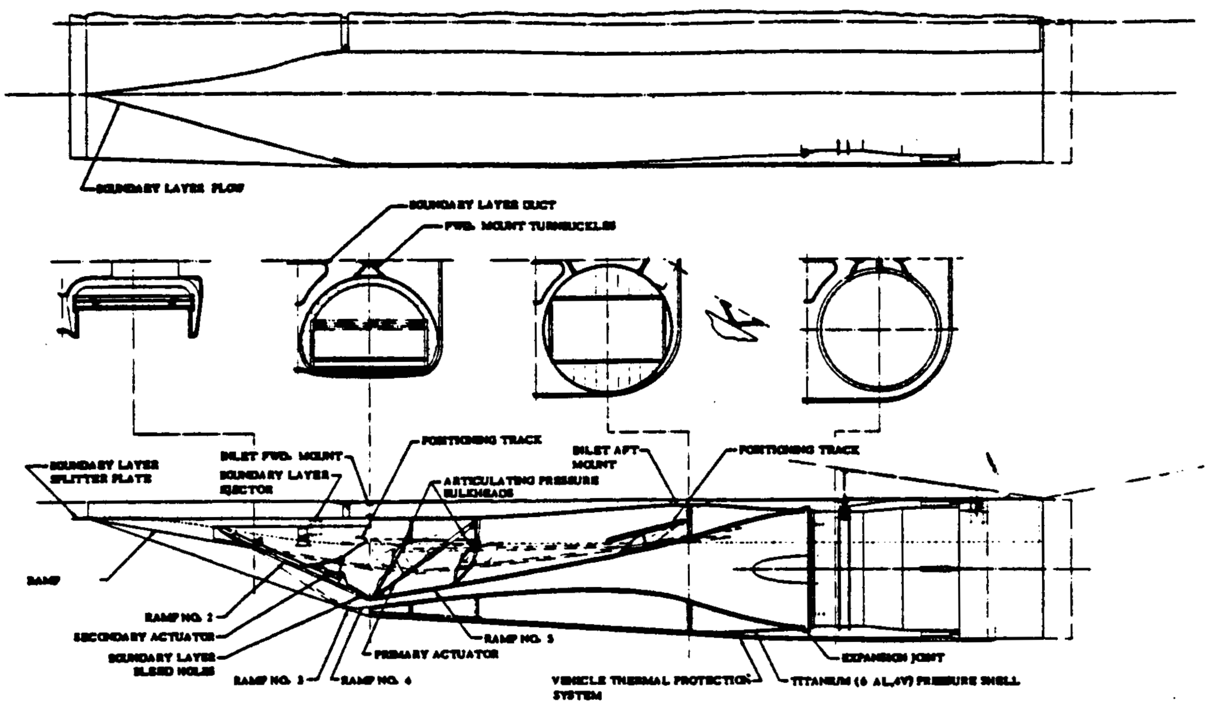


Figure 8. Inlet/Engine Design.

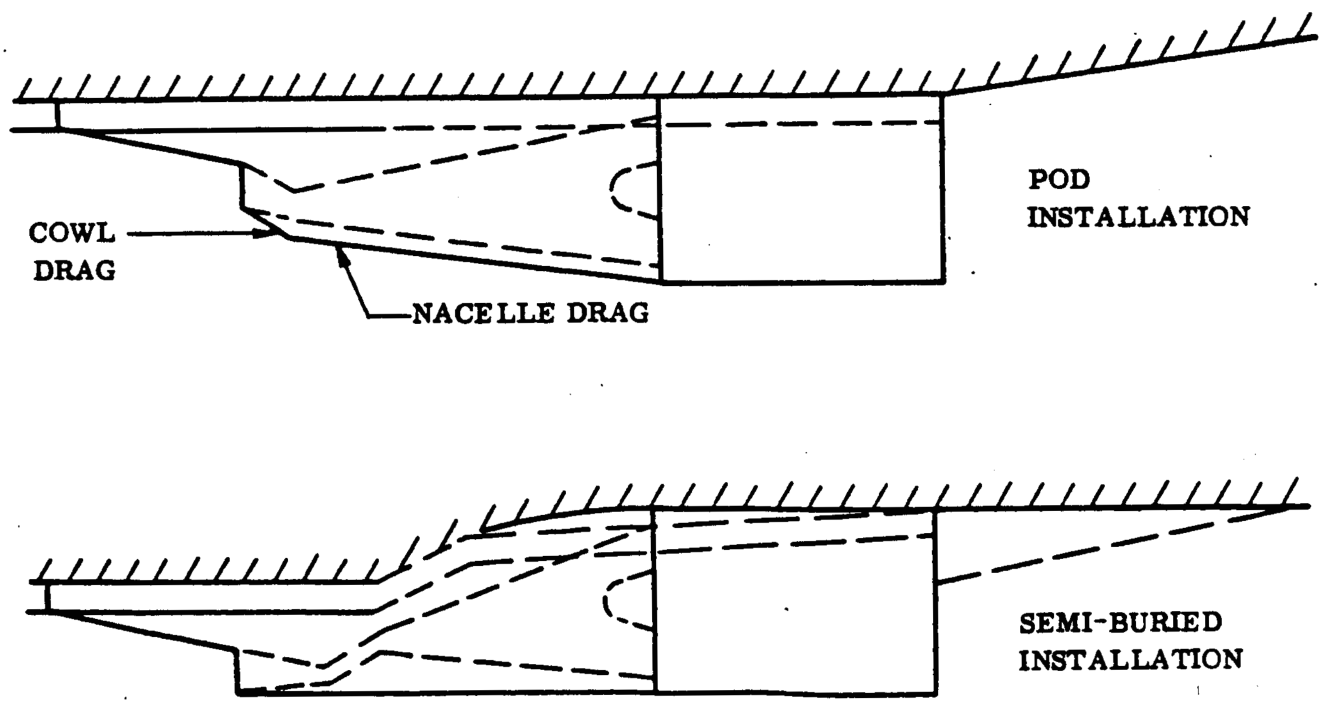


Figure 9. Inlet/Engine Installation.

INSTALLATION ⇨	BEGINNING CRUISE		END CRUISE	
	POD	BURIED	POD	BURIED
FUEL FLOW: COOLING (LB/SEC)	9.35	5.38	8.10	4.71
THRUST	8.39	4.65	7.04	3.96
COOLING/THRUST	1.11	1.16	1.15	1.19
APPROX. CRUISE MACH FOR NO EXCESS FUEL FLOW FOR COOLING	5.5	5.4	5.4	5.3

TABLE 6. PROPULSION COOLING REQUIREMENTS.

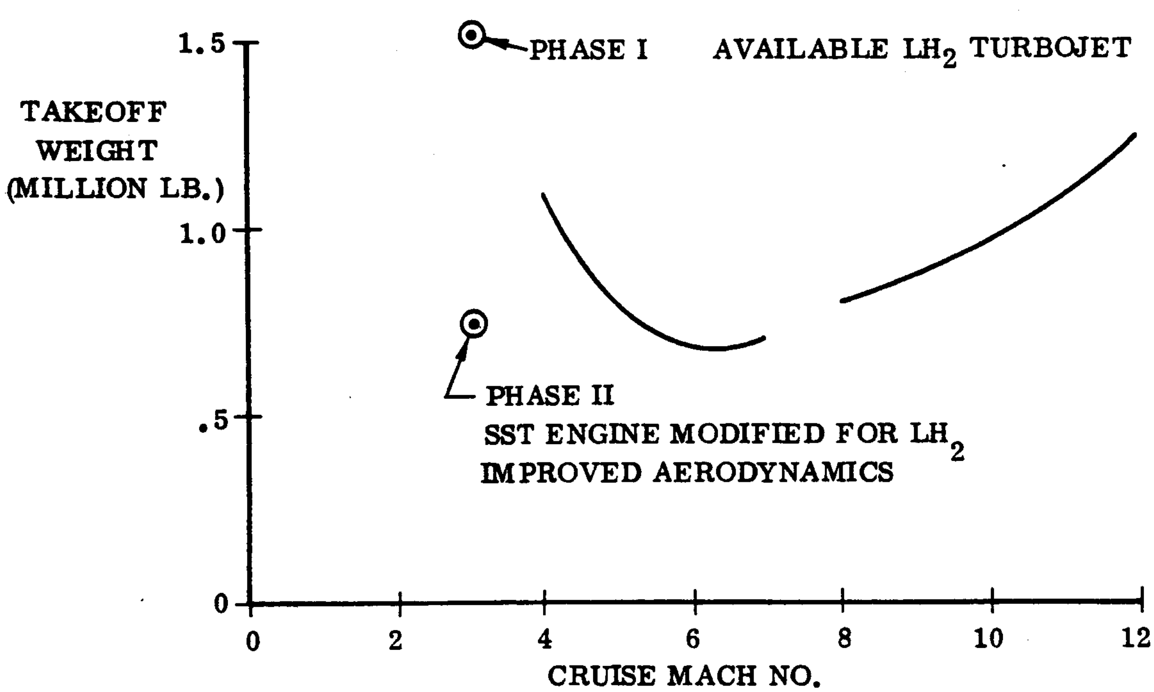


Figure 10. Re-evaluation of Mach 3.0 Cruise.

that has a subsonic specific fuel consumption of about 0.3 to 0.4 lb/hr/lb. This is roughly equivalent to a hydrogen fueled version of the Supersonic Transport engines. A second solution might be to perform the abort mission at Mach 3.0, but this would require improved sfc at Mach 3.0. With suitable redundancy it may be possible to continue at Mach 6.0 in all cases.

Mach 3.0 Cruise

During Phase I, the effect of cruise Mach numbers between 3 and 8 was evaluated by extrapolation of the Mach 6.0 Delta Wing baseline vehicle. During the Phase II studies a point design of a Mach 3.0 cruise vehicle was evaluated. More detailed drag analysis plus changing to the Blended Body configuration improved the maximum lift/drag ratio at Mach 3.0 from 4.5 to 5.6. In addition, a liquid hydrogen fueled version of the Supersonic Transport engine was used, rather than the turbojet portion of a liquid hydrogen fueled, Mach 8.0 turboramjet engine that was used in Phase I. This improved the specific fuel consumption during cruise by 40%. Figure 10 shows that the takeoff weight for Mach 3.0 cruise is about the same as for Mach 6.0 cruise.

Liquid Oxygen vs. Turbomachinery for Transonic Acceleration

Engines which use liquid oxygen/liquid hydrogen rockets with ejector and fan augmentation are characterized by lightweight and high propellant consumption compared with a turbojet. To minimize propellant consumption during climb, the liquid oxygen flow must be cut off at low supersonic Mach numbers. Subsonic hold over the destination airport must be accomplished without the oxygen flow to the rockets (i.e., turbomachinery is required). The best available engine of this type gave a takeoff weight $\approx$ 40% higher than the turbojet - mainly because $\approx$ 20% of the takeoff weight is in liquid oxygen.

Conclusions.

1. A semi-buried engine installation is required to give acceptable values of specific fuel consumption during Mach 6.0 cruise.

2. The available liquid hydrogen turboramjets need excess cooling fuel for cruise at Mach numbers greater than $\approx$ 5.3.

3. A subsonic specific fuel consumption of about 0.3 lb/hr/lb is required to meet the probable subsonic abort requirements.

4. Mach 3.0 cruise is competitive with Mach 6.0 cruise but needs Supersonic Transport type engines.

5. Using liquid oxygen rocket assist during takeoff and transonic acceleration is not competitive with turbojets.

3.4 SONIC BOOM & ENGINE NOISE

The Phase I studies indicated that shaping of the vehicle forebody could reduce the overpressures during climb by about 1 psf. The Phase II studies therefore investigated the effects on overpressure of various forebody shapes. Mach 1.4 at 40,000 ft. was selected as being representative of the peak value of overpressure at about 50 miles downrange from takeoff. Figure 11 shows that if a smooth distribution of the "effective cross section area" (lift plus area) is obtained, then the overpressure during climb can be reduced to about 2 psf. The overpressures for the minimum sonic boom vehicle shape are then a peak of $\approx$ 2 psf at 50 miles from takeoff reducing to $\approx$ 1 psf at 500 miles downrange from takeoff. This 1 psf is then constant until the end of cruise (about 600 miles from the destination) and then peaks up to about 1.7 psf during descent at 100 miles from the destination airport.

Table 7 compares engine data and noise. This shows that for a full thrust takeoff, the engines of the hydrogen fueled transport will develop about 5 db more airport noise than the Supersonic Transport engines. Because of the high takeoff thrust loading and subsequent steep climb path, the hydrogen fueled transport may give less community annoyance at 4 miles from brake release than the Supersonic Transport.

	CONVAIR 880	SUPERSONIC TRANSPORT	HYDROGEN FUELED TRANSPORT
AIRCRAFT WEIGHT (LB)	184,500	500,000	531,200
FULL TAKEOFF THRUST (LB)	41,000	195,000	356,000
OVERALL POWER LEVEL(db)	175	190	195
ALTITUDE @ 4 MILES FROM BRAKE RELEASE (FT)	1,390	2,000	5,000
FLIGHT PATH ANGLE @ 4 MILES	6^{o}	7.25^{o}	13.3^{o}
PERCEIVED NOISE LEVEL (PNdb)	116	121	116

TABLE 7. ENGINE NOISE

3.5 STRUCTURES

Because of the unique features of liquid hydrogen, most of the study effort was spent in defining the significant design conditions for the fuel tanks. The preliminary studies of Phase I showed that integral tanks were lighter than non-integral, and these are shown in Figure 4. Figure 12 shows the two fundamental fuel tank design requirements of:

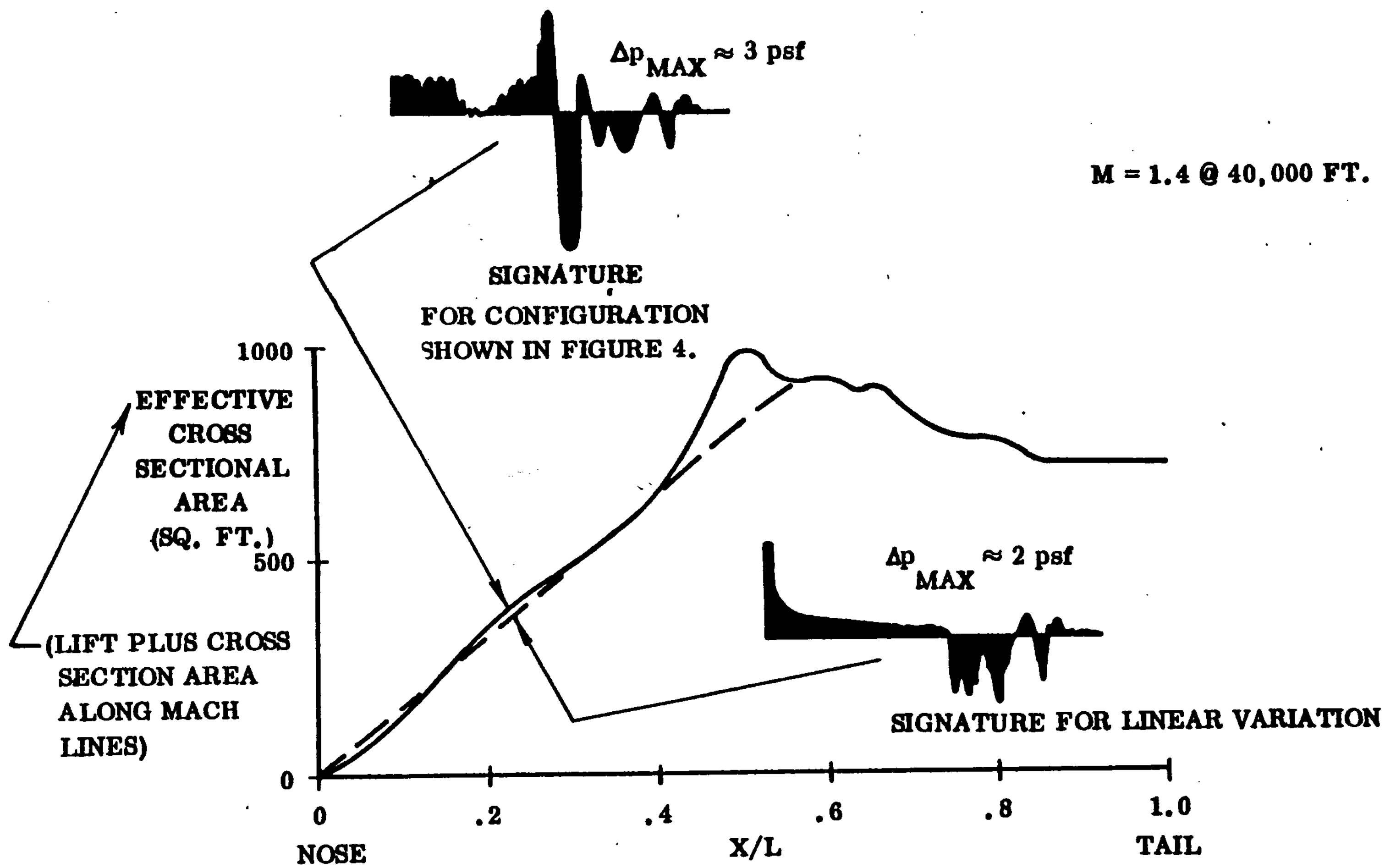
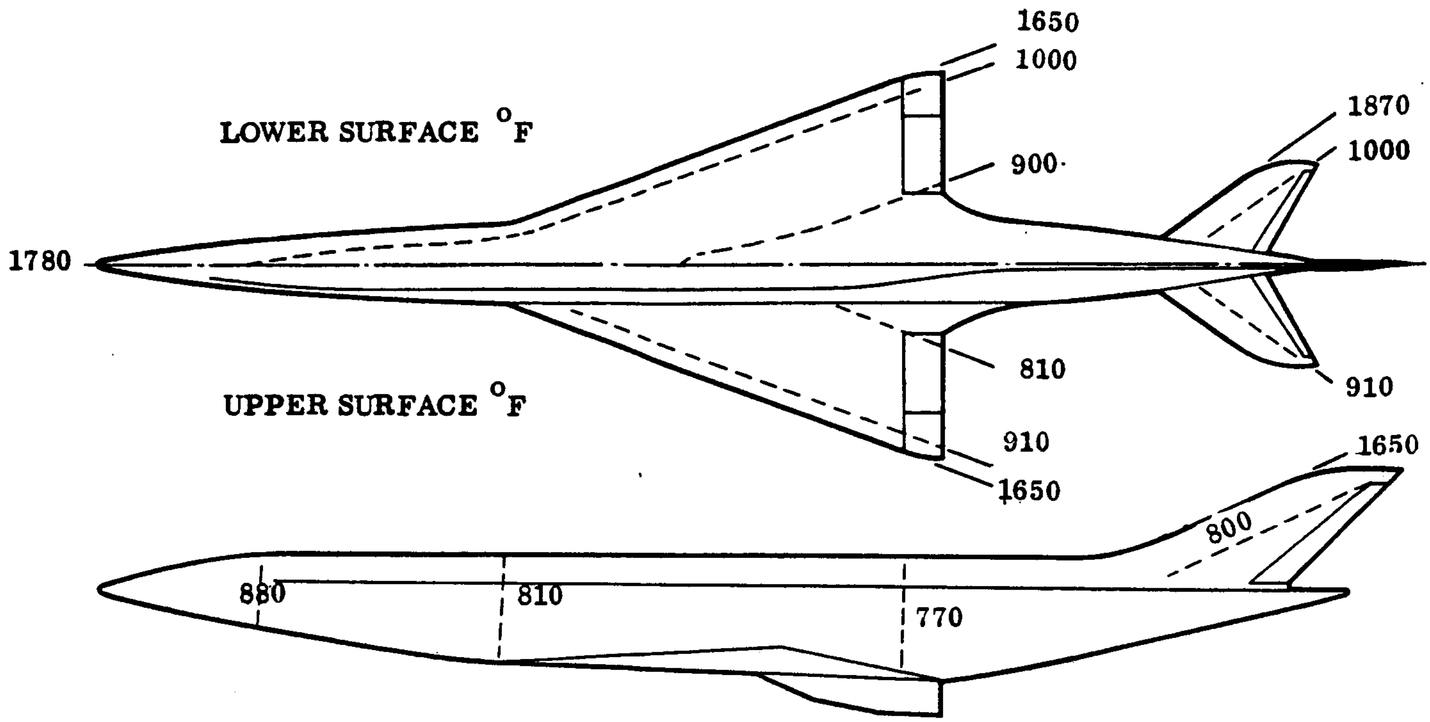


Figure 11. Vehicle Shaping for Minimum Sonic Boom.



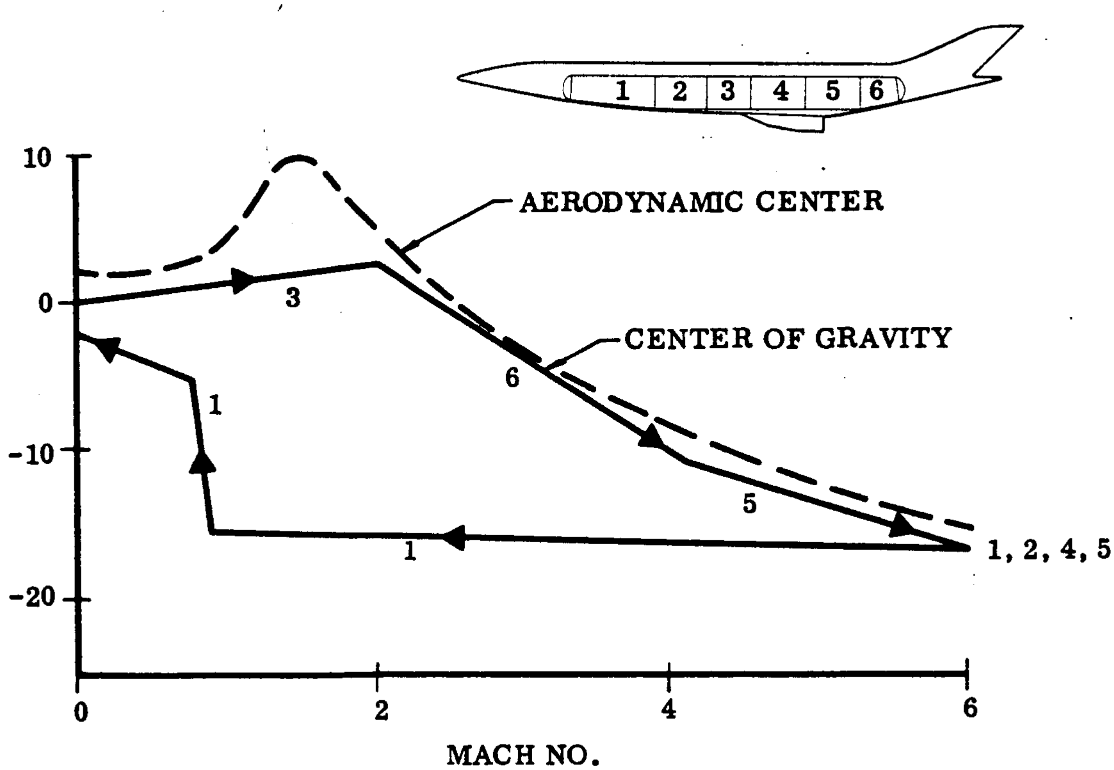


Figure 12. Surface Temperatures and Fuel Tank Sequencing.

(a) Surface temperatures during cruise. Except for the nose and leading edges, the surface temperatures are less than 1,000°F.

(b) Tank sequencing for c.g. control. This is necessary to minimize control surface size, loads and deflections and minimize trim drag. Figure 12 shows that tank No. 3 is empty at Mach 2.0 during the climb (about 8 minutes after takeoff) and remains empty for the rest of the mission. Tank No. 1 represents the other extreme of fuel storage in that it remains full until near the end of cruise and is emptied during descent, loiter and landing.

Because of the tank sequencing (assuming a fibrous insulation/gaseous helium purge system), the dry portions of the tank heat up. This gives temperatures in tank No. 3, that, at the end of cruise, are close to the local skin temperature of the aircraft. In addition, temperature differentials of up to 1,000°F can occur between the top and bottom of the tanks, and a differential of ≈ 1,300°F can occur between tanks.

Minimum weight was achieved with ≈ 2" of insulation on all tanks except ≈ 3" for tank No. 1. This gave ≈ 2% fuel boil off and ≈ 25 psig tank vent pressure.

Safety will probably require a gaseous helium atmosphere around the tanks and fuel system components. Outgassing during the climb and repressurizing during descent will require a complex distribution system. The cost of gaseous helium could amount to 25% of the fuel costs per flight and this indicates that non-gaseous helium systems are desirable.

Including the effects of volume utilization and thermal stresses, integral and non-integral tanks weigh about the same. Additional operational problems associated with integral tanks led to the selection of non-integral tanks as being the most feasible approach.

The most promising structural concepts are shown in Figure 13. The requirements for safety and for the prevention of cryo-pumping is a major problem area for which there is no current, competitive solution. This is an area for basic study and research to find ways of minimizing the consumption of gaseous helium, including CO_2 frost and double tank wall approaches.

3.6 CABIN

Conclusions of the investigation of the cabin were:

(a) An environmental control system can be provided for reasonable weights, with reasonable mission reliability and with provisions to enable safe recovery from potentially catastrophic failures.

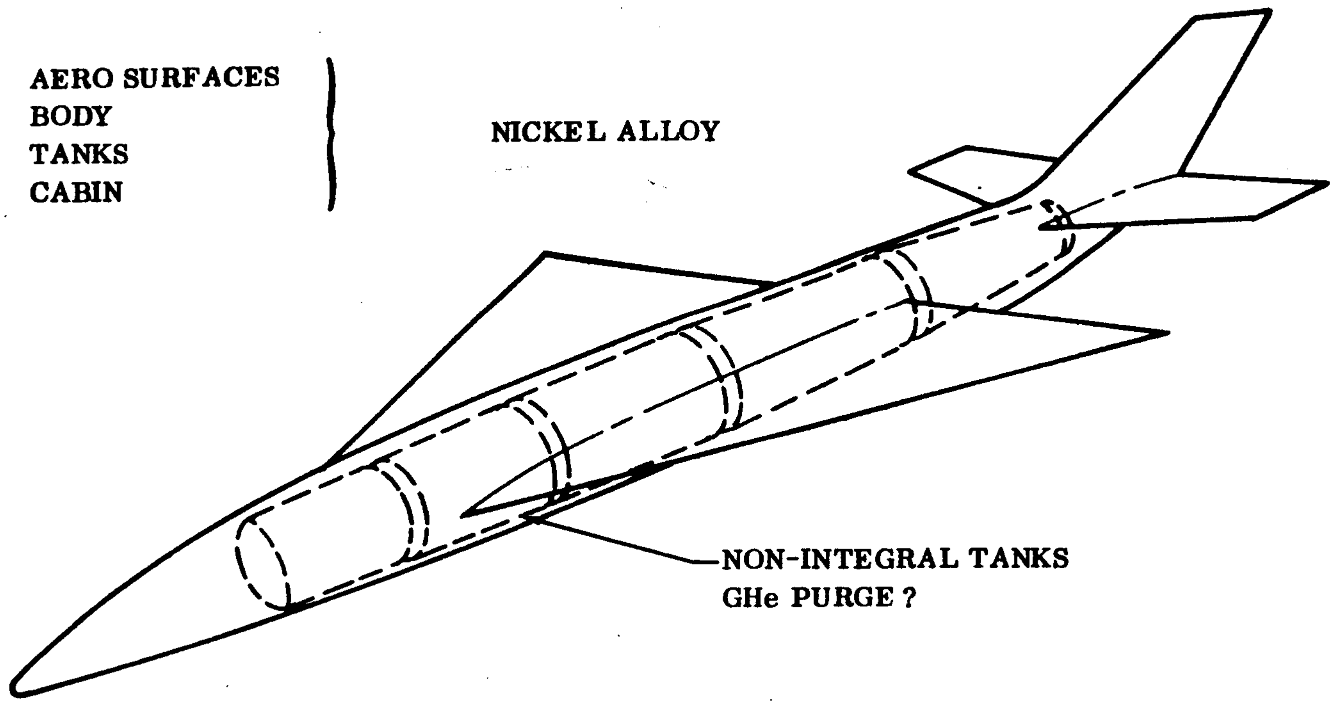


Figure 13. Final Structural Concepts.

(b) Weight trade-offs of passive versus semi-active systems to maintain cabin temperature favored the semi-active approach of 4 inches to 6 inches of insulation with coolant air tubes adjacent to the cabin trim.

(c) The semi-closed loop system was selected. This system can accommodate a cabin rupture (window) and does not require a cabin leak rate that is much better than that achieved on current subsonic jets. However, it has the disadvantage of requiring a heat exchanger designed to handle 3,200°F inlet air. Triple redundancy is required.

(d) Ionizing radiation during cruise is not a serious problem.

3.7 COSTS

For a commercial transport mission, costs are of primary concern. Within the broad scope of this study no detailed cost analysis was performed, however costs were developed to (a) indicate the most promising technical approaches, and (b) to help in defining critical research areas. The two most significant cost items are fuel and airframe as discussed below.

Cost of Liquid Hydrogen

As shown in Figure 14, the present cost of liquid hydrogen is 28 - 30 cents/lb. This gives a direct operating cost of about 8 cents per seat mile compared with about 1-1.5 for current and projected subsonic and supersonic transports. To obtain fuel costs that are comparable with the projected Supersonic Transport, the cost of liquid hydrogen must be reduced from 30 to 3-4 cents/lb.

Airframe

The direct operating cost less fuel (i.e., airframe) is shown in Figure 15 as a function of cruise Mach No. Approximate costs of JP fueled, subsonic and supersonic transports are also shown. It is seen that at Mach 3.0, a liquid hydrogen fueled aircraft is estimated to have twice the direct operating cost of a JP fueled aircraft. This is mainly because of the more sophisticated structural concepts associated with the containment of liquid hydrogen. An additional factor is the less developed technology of liquid hydrogen compared with JP.

4.0 FINAL STUDIES

The final studies were in three areas: final configurations, sensitivity studies and critical research areas. These are discussed in Sections 4.1, 4.2, and 4.3 respectively.

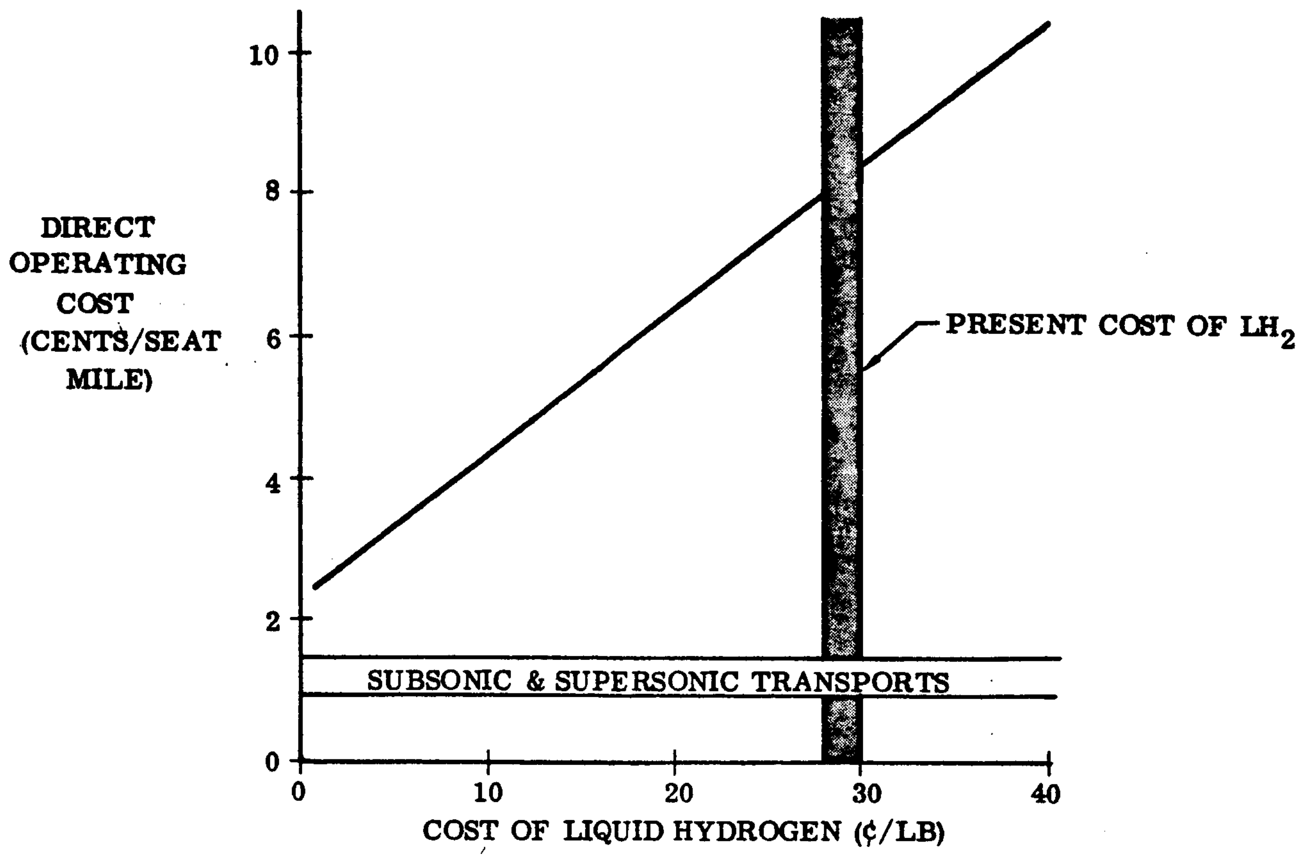


Figure 14. Cost of Liquid Hydrogen.

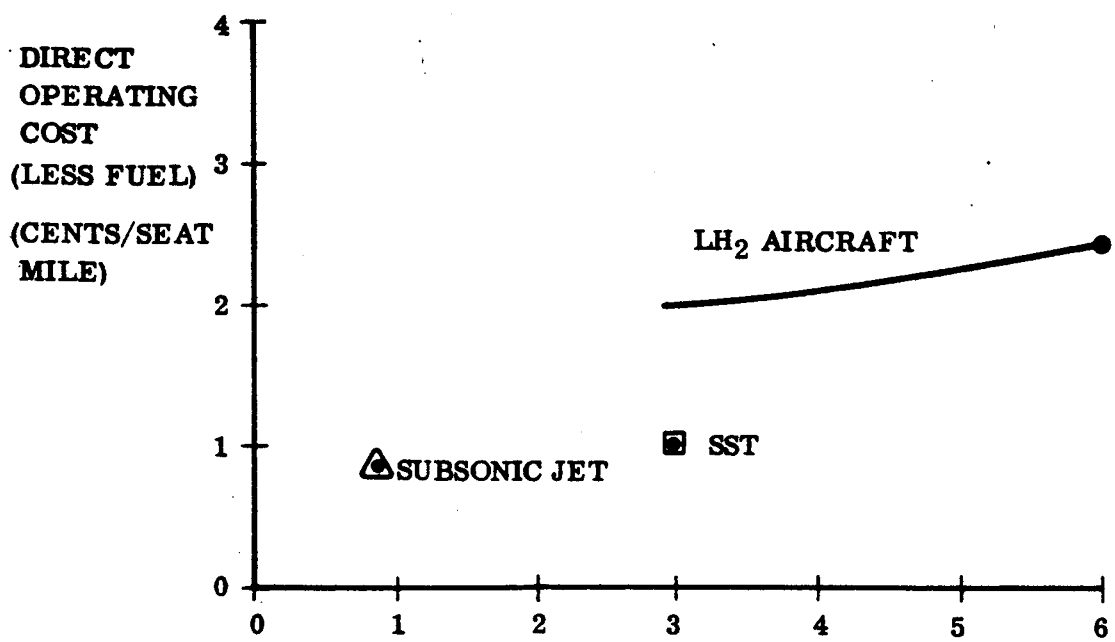


Figure 15. Airframe Cost.

4.1 FINAL CONFIGURATIONS

Table 8 shows a specification for a hydrogen fueled commercial transport that is based on the studies discussed in Section 3.0. Table 9 shows the takeoff weight of the two final configurations and how the takeoff weight varied throughout the study. Figure 16 shows the final configurations that incorporate the results of the studies discussed in Section 3.0.

4.2 SENSITIVITY

Table 10 shows the sensitivity as an increase in takeoff weight for a 1% change in the nominal value of a parameter. It is seen that lift/drag ratio and specific fuel consumption at Mach 6.0 are the most sensitive vehicle parameters. (Subsonic sfc is the most important vehicle parameter if the abort mission is required.)

4.3 CRITICAL RESEARCH AREAS

In order of severity, the most critical research areas are:

1. Cost of liquid hydrogen

   To get fuel costs that are comparable with the Supersonic Transport, the delivered cost of liquid hydrogen must be about 3-4 cents/lb compared with about 30 cents/lb today. In addition, the electricity and natural gas consumption to produce the liquid hydrogen for 200 flights per day is roughly equal to 10 percent of the present electrical capacity and natural gas consumption of the United States.

2. Propulsion

   The studies show that basic cycle tradeoffs of subsonic sfc vs. transonic thrust/engine weight are required to better meet the probable subsonic abort requirements of an sfc $\approx$ 0.3 lb/hr/lb. Cruise sfc was shown to be the most sensitive vehicle parameter. This requires a buried installation to limit the frontal area of the engine which is about twice that of the inlet cowl. Engine/inlet cooling during cruise requires either a radical redesign of the integrated turboramjet engine or a reduction of cruise Mach No. from 6.0 to about 5.3.

3. Structure

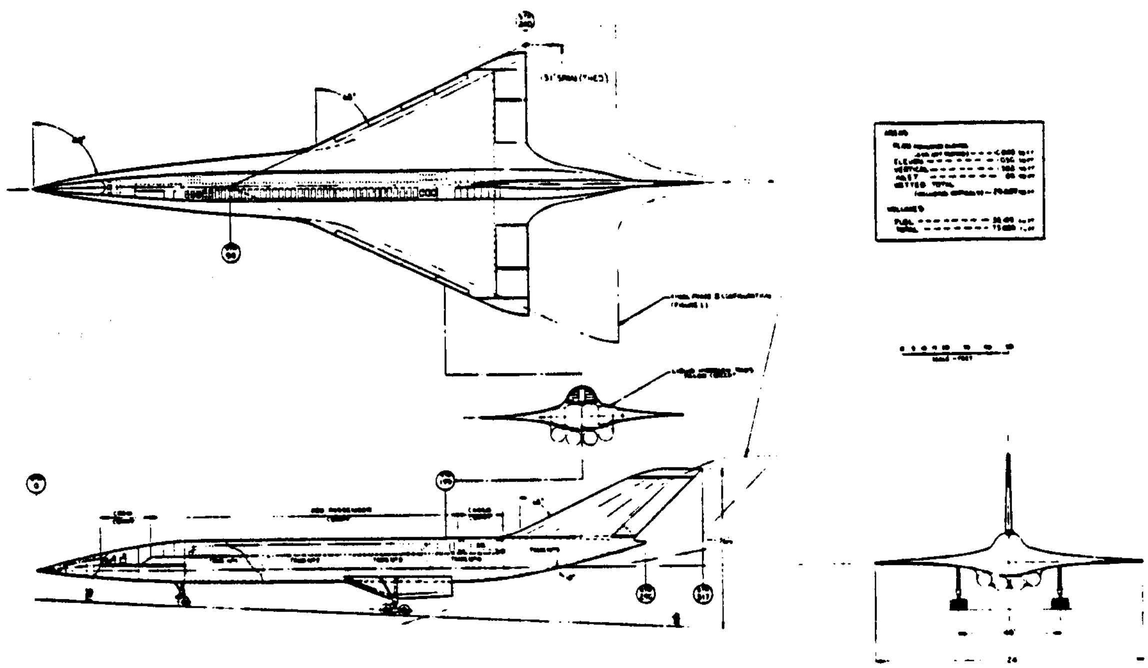
   The most challenging area of the structure is that associated with insulating the fuel tanks. There is no known concept that meets the cost and turnaround requirements of a commercial transport. Tank sequencing, tank thermal differentials, condensation, cryo-pumping, safety, ambient pressure variations throughout the flight and cost are the important criteria that must be included in a fundamental study of insulation concepts.

RANGE	1, 500 - 5, 000 N. MI.
PASSENGER	200
SONIC BOOM	2 PSF OVERPRESSURE DURING CLIMB <1 PSF DURING CRUISE
LOITER/HOLD	1, 000 SECS. & 100 N. MI. @ M = 0. 9 @ 40, 000 FT.
ABORT	2, 500 N. MI. @ M = 0. 9
PROPULSION	SEMI-BURIED INSTALLATION CRUISE MACH 6 (PROBLEMS = COOLING & SUBSONIC SFC)
STRUCTURE	NON-INTEGRAL TANKS (PROBLEMS = INSULATION) NICKEL ALLOY HOT STRUCTURE
CONFIGURATIONS	BLENDED BODY & DELTA WING

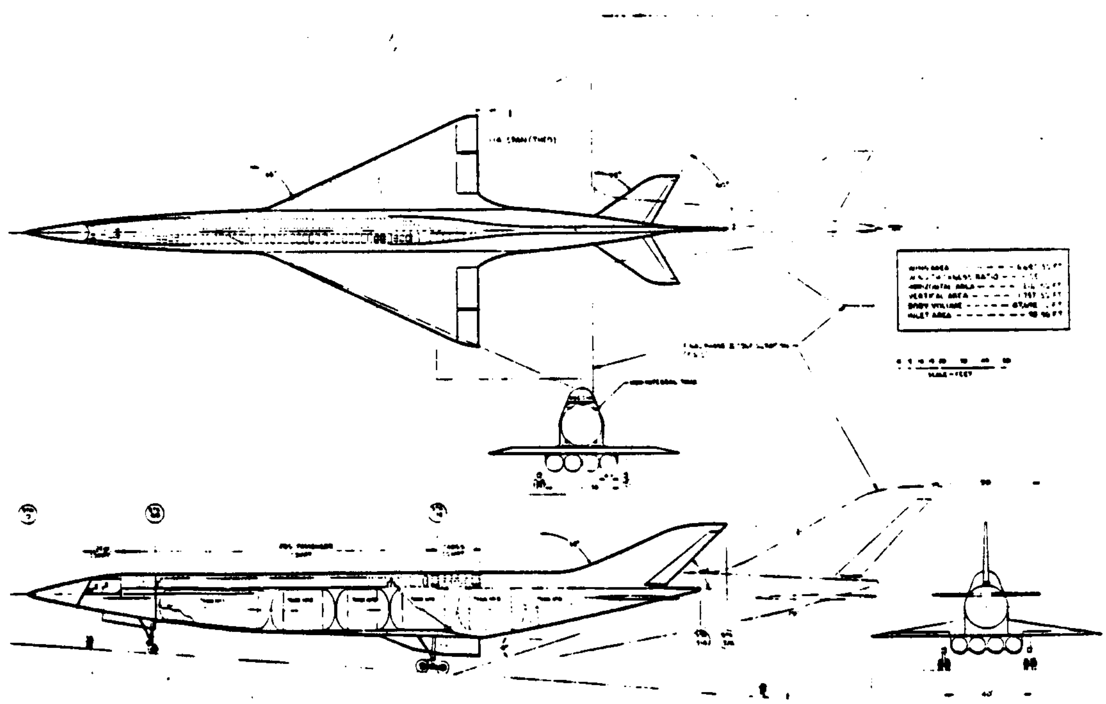
TABLE 8. FINAL CONFIGURATION SPECIFICATION.

	BLENDED BODY CONFIGURATION	DELTA WING CONFIGURATION
FINAL PHASE I	543, 797	537, 040
FINAL PHASE II	636, 851	1, 022, 621
FINAL PHASE II (BURIED PROP'N.)	512, 300	750, 837
PROJECTED STATE-OF-THE-ART	401, 637	521, 046
MACH 3.0 CRUISE (PROJECTED)	410, 934 LB.	

TABLE 9. TAKEOFF WEIGHTS.



BLENDED BODY CONFIGURATION



DELTA WING CONFIGURATION

Figure 16. Final Configurations.

	LB. TAKEOFF WEIGHT / % CHANGE IN PARAMETER
DESIGN RANGE	8,500 (1.32)*
LIFT/DRAG RATIO AT MACH 6.0 SPECIFIC FUEL CONSUMPTION AT MACH 6.0	6,000 (.95)
TRANSONIC DRAG	3,900 (.61)
BODY STRUCTURE WEIGHT	3,800 (.60)
PASSENGER CAPACITY	3,100 (.49)
ENGINE WEIGHT/SLS THRUST	2,040 (.32)
FUEL TANK WEIGHT	1,530 (.24)
SUBSONIC LOITER LIFT/DRAG RATIO SUBSONIC LOITER SPECIFIC FUEL CONSUMP.	1,220 (.19)
SUBSONIC SFC (ABORT MISSION)	11,300 (1.78)

$* \frac{\text{\% Change in takeoff weight}}{\text{\% Change in parameter}}$

TABLE 10. SENSITIVITY DATA

4. Aerodynamics

Most of the aerodynamic analytical techniques at Mach 6.0 are extensions of Mach 3.0 theories. These require validation. A configuration evolution, similar to that conducted for the Supersonic Transport, is required.

5.0 STUDY CONCLUSIONS & OBSERVATIONS

The most significant conclusions from this study are shown below:

1. Projected Passenger Traffic

   From the passenger traffic patterns projected to the year 2000, 50% of the international passengers will be flying across the North Atlantic at a range of about 3,200 nautical miles. Approximately 80% of the international passengers will be travelling at ranges of less than 5,000 nautical miles, and 90% at ranges less than 6,000 nautical miles.

2. Design Range and Cruise Mach No.

   Because of the passengers traffic distribution discussed in 1 above, a design range of 5,000 nautical miles is a reasonable compromise between takeoff weight, sonic boom and cost.

   For a hydrogen fueled transport, the best cruise Mach No. is about 6.0. Higher speeds than this are less desirable because of (a) higher takeoff weight (= higher cost), (b) diminishing saving in trip time for the 5,000 nautical mile range, (c) local times of arrival and departure (for the predominantly east/west traffic) are not improved by higher speeds.

   Mach 3.0 cruise could be more economical than Mach 6.0 because of significantly less engine development costs.

3. Configurations

   Because the liquid hydrogen fuel dominates the volume requirements, the passenger cabin may be placed in an unconventional location (for instance in a three story compartment adjacent to the c.g. of the aircraft). Safety during flight and emergency ground exit are significant problems (currently the passengers are 30'-40' above the ground).

   Efficient containment of the fuel is undoubtedly the most significant structural item. However, the structural requirements are compromised by aerodynamics, propulsion installation, passengers and crew, as well as landing gear. The Blended Body shape seems to be the layout that offers the best compromise between these conflicting requirements.

4. Costs

A detailed cost analysis was not performed. However, based on the elementary cost data that were generated, the most critical aspect of a hydrogen fueled transport is its economics. Airframe costs (direct operating costs) may be 2-3 times that of a JP fueled aircraft because of the more advanced technology associated with liquid hydrogen, although some of the difference is undoubtedly due to the infant technology of liquid hydrogen systems.

In addition, the most critical research area is that associated with the production of large quantities of liquid hydrogen at about one-tenth of today's cost of 30 cents per pound.

5. Propulsion System and Structure

These two technical areas were shown to have fundamental technical problem areas. Both the propulsion and structure require solutions that are significantly different from any existing approaches. This is primarily because neither of these two technical areas have been studied for the stringent requirements of a commercial transport. Although this study had negative conclusions on the available propulsion systems and structural approaches, specifications for the required characteristics were included. It is felt that with study of the indicated approaches acceptable solutions will be obtained.